

A Very Small and Super Strong Zebra Pattern Burst at the Beginning of a Solar Flare

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ABSTRACT

Microwave emission with spectral zebra pattern structures (ZPs) is observed frequently in solar flares and the Crab pulsar. The previous observations show that ZP is only a structure overlapped on the underlying broadband continuum with slight increments and decrements. This work reports an extremely unusual strong ZP burst occurring just at the beginning of a solar flare observed simultaneously by two radio telescopes located in China and Czech Republic and by the extreme ultraviolet (EUV) telescope on board NASA's satellite Solar Dynamics Observatory on 2013 April 11. It is a very short and super strong explosion whose intensity exceeds several times that of the underlying flaring broadband continuum emission, lasting for just 18 s. EUV images show that the flare starts from several small flare bursting points (FBPs). There is a sudden EUV flash with extra enhancement in one of these FBPs during the ZP burst. Analysis indicates that the ZP burst accompanying EUV flash is an unusual explosion revealing a strong coherent process with rapid particle acceleration, violent energy release, and fast plasma heating simultaneously in a small region with short duration just at the beginning of the flare.

Subject headings: Sun: activity — Sun: flares — Sun: particle emission — Sun: radio radiation

1. Introduction

Microwave bursts are frequently observed from the Sun (Elgaroy 1959; Tanaka & Enome 1970; Dulk 1985; Bastian, Benz, & Gary 1998), flare stars (Bastian et al. 1990), neutron stars (McLaughlin et al. 2006), and even the Crab pulsar (Hankins & Eilek 2007). Spectral fine structures in microwave bursts are believed to contain abundant information of particle acceleration, energy release, and other non-thermal processes in magnetized astrophysical plasmas. In particular the microwave zebra pattern (ZP), a kind of fine structure superposed on the solar radio broadband continuum spectrogram, which consists of several almost parallel and equidistant stripes. It is an interesting and intriguing phenomenon, which may reveal the original information of the flaring source region, such as the magnetic field and its

configurations, particle acceleration, and plasma instabilities in the source region where the energy release takes place (Kuijpers 1975; Chernov et al. 2005; Tan et al. 2012; Chernov 2006; Hankins & Eilek 2007; Karlický 2013). So far, the nature and formation mechanism of microwave ZP structures is still a controversial problem which has been discussed widely for more than 40 years (Rosenberg & Tarnstrom 1972; Zheleznyakov & Zlotnik 1975; Fomichev & Fainshtein 1981; LaBelle et al. 2003; Tan 2010; Chen et al. 2011). According to a recent statistical classification, microwave ZPs can be sorted into three types, and different type will reveal different physical non-thermal processes by different mechanism (Tan et al. 2014).

In the previous observations, the microwave ZP is always only a structure overlapped on the underlying broadband continuum with slight increments and decrements. This work reports an ex-

tremely unusual ZP burst just at the beginning of a solar flare observed simultaneously by two radio telescopes located in China and Czech Republic and by the extreme ultraviolet (EUV) telescope on board NASA's satellite Solar Dynamics Observatory (SDO). It is a very short and super strong explosion which may reveal a rapid particle acceleration and fast plasma heating in a small region and in a short time. Section 2 presents the observations and physical analysis, and Section 3 is the conclusion and some discussions.

2. Observations and Physical Analysis

2.1. Observation data

In this work, observation data are obtained from the following instruments:

(1) The Chinese Solar Broadband Radio Spectrometers at Huairou (SBRs/Huairou)

SBRs is an advanced solar radio telescope with broad frequency bandwidth, and super high temporal- and spectral-resolutions, which can distinguish super fine structures from the spectrogram (Fu et al. 1995, 2004; Yan et al. 2002). Its daily observational window is 0:00-8:00 UT during winter seasons and 23:00-9:00 UT during summer seasons. It includes three parts: 1.10 - 2.06 GHz (with antenna diameter of 7.0 m), 2.60 - 3.80 GHz (with antenna diameter of 3.2 m), and 5.20 - 7.60 GHz (share the same antenna of the second part). The antenna points to the solar disk center automatically controlled by a computer. The spectrometer receives the total flux of solar radio emission with dual circular polarization (left- and right-handed circular polarization, LCP and RCP), and the dynamic range is 10 dB above the quiet solar background emission. The observation sensitivity is: $S/S_{\odot} \leq 2\%$, here S_{\odot} is the quiet solar background emission. In this work we use the observation data at frequency of 2.60 - 3.80 GHz with cadence of 8 ms and frequency resolution of 10 MHz.

(2) Ondřejov radiospectrograph in the Czech Republic (ORSC/Ondřejov)

ORSC is a broadband spectrometer located at Ondřejov, the Czech Republic. It receives solar radio total flux at frequencies of 0.80 - 5.00 GHz during 2000 - 2013 (Jiříčka et al. 1993). Its daily observational window is 7:00 - 16:00 UT in winter

seasons and 6:00 - 17:00 UT in summer seasons. In this work we use the observation data at frequency of 2.00 - 5.00 GHz with a cadence of 10 ms and a frequency resolution of 12 MHz.

SBRs/Huairou and ORSC/Ondřejov have an overlapping observational window 7:00 - 8:00 UT during winter seasons and 6:00-9:00 UT during summer seasons. This common window provides a good opportunity to observe some solar eruptions simultaneously.

(3) Atmospheric Imaging Assembly (AIA) on board NASA's satellite Solar Dynamics Observatory (SDO)

AIA obtains the full-disk snapshot images of the solar corona and transition region with a cadence of 12 s and pixel size of $0.6''$ at UV and EUV wavelengths centered on specific lines: 1700 Å, 1600 Å, 335 Å, 304 Å, 211 Å, 193 Å, 171 Å, 131 Å, and 94 Å. They are formed at different temperatures in the solar chromospheric and coronal plasmas (Lemen et al. 2012), and can present the detailed configurations and fast variations of solar chromosphere and corona.

(4) Soft X-ray (SXR) telescope on Geostationary Operational Environment Satellites (GOES)

The GOES provides continuous monitoring of integrated full-disk solar SXR intensity at 0.5-4 Å channel and 1-8 Å channel with cadence of 3 s. It is the most important indicator to show solar flare processes.

2.2. Main Results

2.2.1. Microwave Spectral Observation

The left panel of Fig.1 presents the microwave spectrograms observed by SBRs/Huairou at LCP and RCP. It shows that there is a bright patch at frequency of 2.65 - 3.10 GHz during 06:58:26 - 06:58:44 UT, just at the very beginning of an M6.5 class flare. This panel is an expanding one showing that the bright patch is similar to a ZP structure which lasts for about 18 s, has 4 curved stripes. The central frequency is 2.87 GHz. The frequency separation of adjacent stripes is about 90 MHz, approximately a constant. The frequency bandwidth of the whole structure is 450 MHz, and the relative bandwidth is 15%. The comparison between RCP and LCP indicates that the bright patch burst is moderate LCP with polarization de-

gree of about 35%. However, we have not enough confidence to confirm it as a ZP structure because there are several bad frequency channels on the spectrogram observed by SBRs/Huairou.

It is very lucky that ORSC/Ondřejov observed also the same microwave burst without any influence of bad frequency channels. The right-upper panel of Fig.1 is the whole spectrogram at frequency of 2.00 - 5.00 GHz during 06:55 - 07:20 UT. Here, we find a broadband microwave continuum burst occurring from the beginning of the flare and lasting to after the flare maximum in the whole frequency range of the spectrometer. The most highlighted is that there is a small and extremely bright patch overlapped on the broadband continuum spectrogram which is marked in a white box. The enlarged spectrogram of the bright patch is presented in the right-bottom panel of Fig. 1. It is much clearer than the spectrogram observed by SBRs/Huairou. Here, we find again that the bright patch consists of four crescent-shaped stripes, and the frequency range, stripe separations, brightness, duration, and the shapes of each stripe are strictly identical to the spectrogram obtained by SBRs/Huairou. These properties show that this spectral structure is most coinciding with a ZP phenomenon, different from the other stripe-like spectral events, such as fiber bursts, lace bursts, and fundamental-harmonic structures (Huang & Tan 2012) etc. Fiber bursts are always with constant frequency drifting rates and random frequency separations (Bernold & Treumann 1983, Wang & Zhong 2006). Lace burst has only one or two stripes with rapid variations of frequency drifting rates (Karlický et al. 2001). The fundamental-harmonic structures generally has only two or three stripes and frequencies are in harmonic ratio (Stahli, Magun, & Schanda, 1987). Additionally, scrutinizing analysis shows that each stripe is composed of many millisecond spike bursts. It is a complicated structure of ZP and spike bursts. This is the first time that an identical microwave ZP structure observed simultaneously by two separate telescopes away from more than seven thousand kilometers. Here, once again, it shows that the zebra event is an extremely strong burst which is much brighter than the basal flaring continuum radiation.

The previous observations show that stripes of microwave ZPs always have only a little emission

enhancements and decrements superposed on the basal flaring broadband continuum (see the review of Chernov 2006). Different from the previous observations, the most unusual property of the ZP event here is that it is a super strong and isolated burst. Fig.2 presents the profiles of microwave emission fluxes at the central frequency (2.87 GHz) of the ZP structure at LCP and RCP obtained by SBRs/Huairou, the total flux obtained by ORSC/Ondřejov, and SXR at 1-8 Å obtained by GOES during the flare. SXR observations show that the flare takes place in active region NOAA 11719 located very close to the solar disk center. It is a two-ribbon M6.5 class flare, starts at 06:58 UT, reaches to maximum at 07:16 UT, and ends at 07:26 UT. The ZP event occurs just at the beginning of the flare. Its maximum emission flux is so strong that exceeds several times of the basal flaring continuum intensity. The total flux reaches to 1350 sfu (sfu is the solar radio flux unit, $1 \text{ sfu} = 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$), while the flaring continuum emission flux before and after the ZP burst is only about 200 sfu, the net intensity of the ZP event is about 1150 sfu. From the bandwidth and intensity, the emission brightness temperature can be estimated as 2.10×10^{11} K. It is so strong that only coherent mechanism can produce it. Therefore, we call such explosion as ZP burst.

As a comparison, there are several microwave type III bursts occurring about 2 minutes after the ZP burst, but their intensities are much weaker than the ZP burst, see the bottom panel of Fig. 4.

2.2.2. EUV Imaging Observation

Although we know a super strong microwave ZP burst taking place at the beginning of the flare, but we do not know the location of the source region and its configuration for lack of imaging observations at the corresponding frequencies up to now. Similar to the solar microwave emission, EUV emissions also have source regions locating from chromosphere to the lower corona, it is possible to get some indirect information of the source region of the ZP burst from scrutinizing of the EUV snapshot imaging observations obtained by AIA/SDO in the same duration.

The snapshot imaging observations show that the flaring region brightens up continuously from the flare onset (06:58 UT) to its maximum (07:16

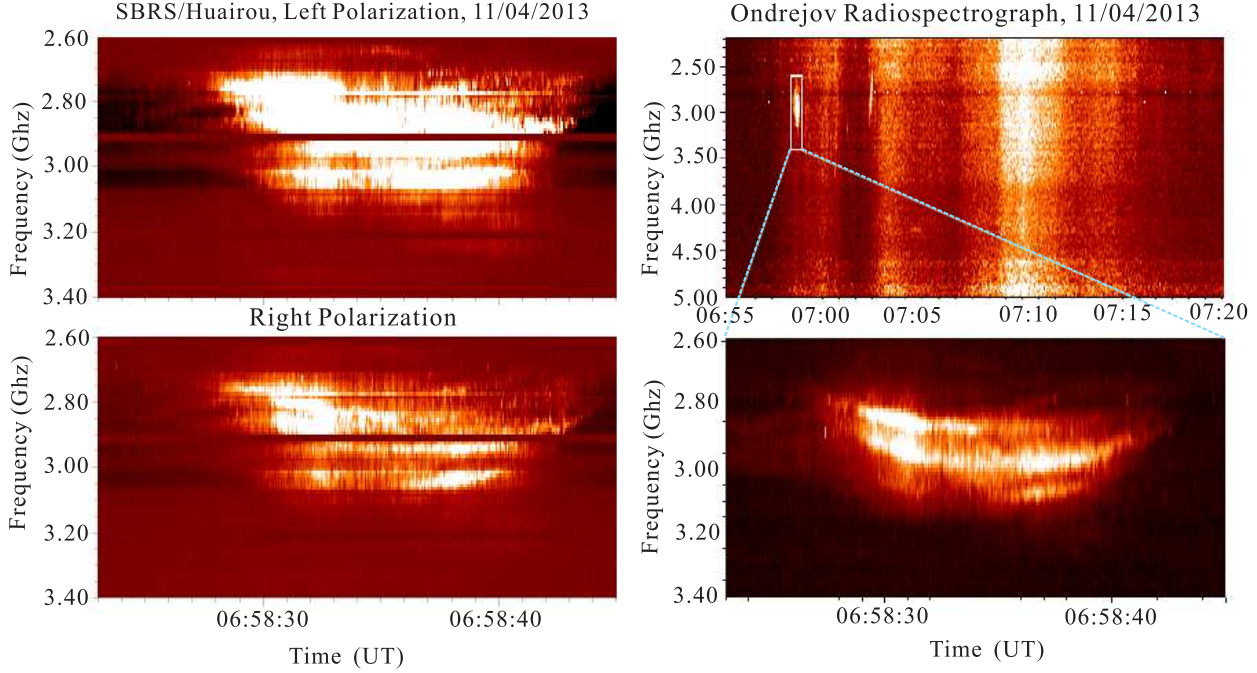


Fig. 1.— Spectrograms of the microwave zebra pattern burst at the beginning of an M6.5 flare on 2013 April 11. The left panels are obtained by the Chinese Solar Broadband Radio Spectrometers at Huairou at left- and right-handed circular polarization. Right panel is obtained by the Ondřejov radiospectrograph in the Czech Republic.

UT) at UV and EUV wavelengths. There are two reversed S-shaped ribbons during the flaring process. The scrutinizing of the snapshot images reveals that the flaring ribbons are consisting of several separated small bright points before the flare onset at almost all UV and EUV wavelengths. The white arrows in left-upper panel of Fig.3 indicate such bright points occurring before the flare onset. At the initial phase, bright points are very small and separated from each other. Then they become larger and larger gradually. Finally, they connected with each other and form two bright reversed S-shape ribbons. We call such bright points as flare bursting points (FBPs).

Among these FBPs, it is most interesting that there is one which has a sudden strong extra enhancement at EUV wavelengths overlapped on the background continuously brightening just during the above microwave ZP burst. This FBP locates at the middle of one ribbon centered in the flaring region (marked *P* and a long yellow arrow in the white box). Fig.3 presents images observed

at 211 Å at four different moments. Before the ZP burst it is just a small bright point (left-upper panel, at 06:57:37 UT). During the ZP burst it becomes so strong that the emission exceeds the saturation level (right-upper panel, at 06:58:25 UT). At the end of the ZP burst its brightness decreases slightly but the area enlarges obviously (left-bottom panel, 06:58:49 UT). After the ZP burst, it continues to brighten up along with the evolution of the flare process.

Besides images of 211 Å, the similar extra enhancements are also occurring at wavelengths of 171 Å, 193 Å and 304 Å in the same region with saturations. However, different EUV wavelengths will saturate at different levels for their different emission strengths. The images at 94 Å, 131 Å and 335 Å have a moderate extra enhancement with respect to its background continuous brightening although they do not exceed the saturation level in the above small region. We call all of these small sudden strong enhancements at EUV wavelengths as EUV flash. The width of the

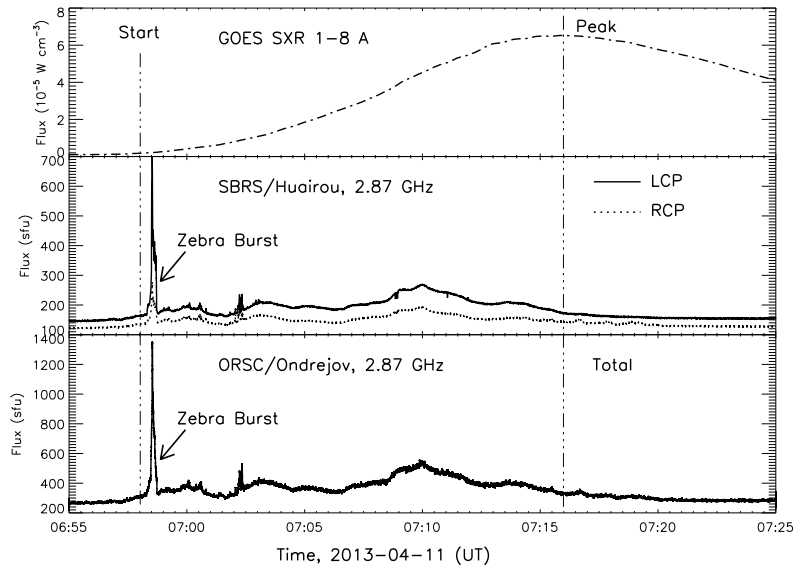


Fig. 2.— Profiles of microwave emission intensities at 2.87 GHz at left- and right-handed circular polarization (LCP and RCP) observed by SBRS/Huairou and by ORSC/Ondřejov (total), and the GOES soft X-ray intensities at 1 - 8 Å (SXR) in the M6.5 flare on 2013 April 11. It shows that the zebra burst is so strong that it exceeds several times of the basal flaring continuum emission.

EUV flash region is less than $3''$ (< 2200 km) and the length is less than $7''$ (< 5000 km). It lasts for < 24 s which is very close to the duration of the above ZP burst.

In order to show the emission variations at different wavelengths in the above small region, Fig. 4 plots profiles of the integral emission intensity calculating at different EUV wavelengths in a rectangle box surrounding the above EUV flash FBP (white box in Fig. 3) during 06:55 - 07:05 UT. As a comparison, the profile of microwave emission at the central frequency of the ZP structure (2.87 GHz) is also overplotted in Fig. 4. Here we find that all profiles increase continuously along with the flaring process. It is reasonable because the small EUV flash region is just located near the center of the flaring region, and the period is just at the flare initial rising phase. The most important is that there are some extra enhancements on the profiles at wavelengths of 171 Å, 193 Å, 211 Å and 335 Å during the ZP burst which exceed the background gradual increments (upper panel of Fig. 4). Here, the extra enhancement at 94 Å, 131 Å and 304 Å is not so obvious as above

wavelengths. Of course, in above calculation, the rectangle box is slightly larger than the EUV flash region, the integration may smooth the variations of EUV emission to some extent. The cadence is only 12 s (24 s sometimes), the above results only reflect approximately the variations during the ZP burst at different EUV wavelengths.

2.3. Physical Analysis

The EUV flash indicates that the emission has a sharp extra enhancement in a small region during the microwave ZP burst. It is well-known that different EUV emission lines may have different formation temperatures produced in solar chromosphere and corona (Lemen et al. 2012). The EUV emission intensity is proportional to the square of plasma density and the gradient of temperature. It is only the short rapid heating by energetic electrons that can produce a sharp enhancement of EUV emissions (Tandberg-Hanssen & Emslie 1988). The simultaneity between EUV flash and ZP burst implies that the source region of the ZP burst is most possibly very close to the small EUV flash with a temperature from several

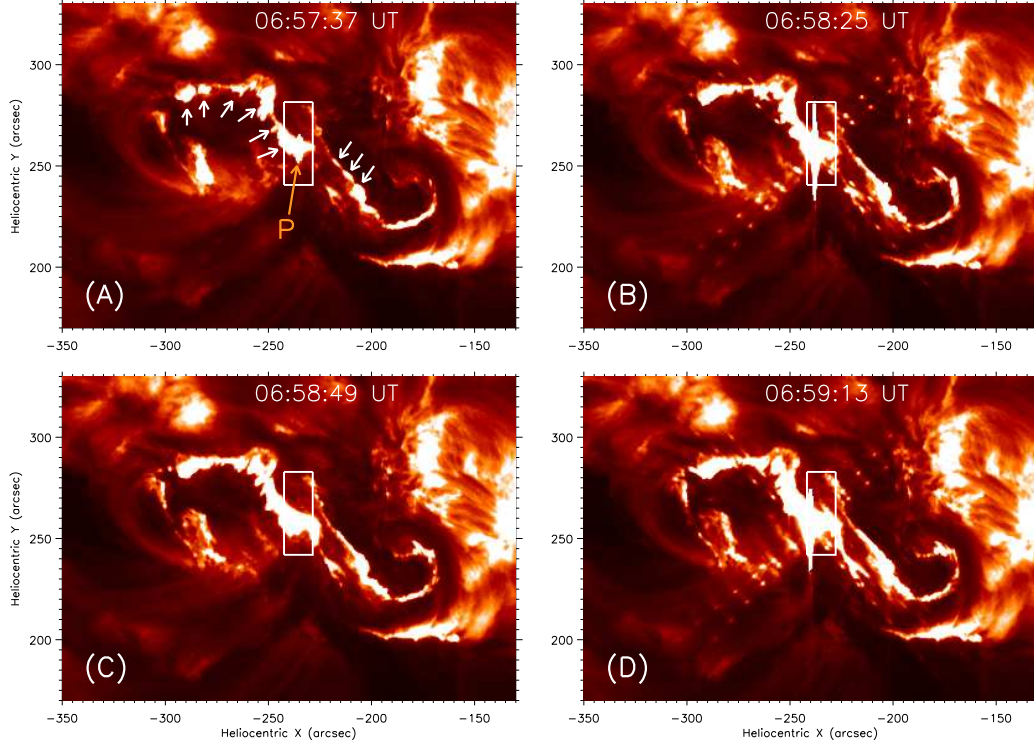


Fig. 3.— EUV images at 211 Å during the ZP burst obtained by AIA/SDO on 2013 April 11. White arrows in panel (A) show EUV bright points before the flare onset. They gradually connect with each other and form the bright flare ribbons after the flare onset showing in panel (B), (C), and (D). Among these bright points, there is a sudden EUV flash during the ZP burst in the white box marked in a yellow arrow (P).

decades of thousand K (such as at 304 Å) up to 10^7 K (193 Å etc).

From the width and length of the EUV flash and the microwave intensity of the ZP burst, we can obtain another estimation of the emission brightness temperature: 1.84×10^{11} K, which is very close to the above result (2.10×10^{11} K) obtained from the frequency bandwidth and the intensity of the ZP burst. Both estimations of the brightness temperatures exceed 5 orders of magnitude of the plasma thermal temperature, and this implies that the microwave ZP burst is a coherent emission process, which can amplify the initial fluctuations over several orders of magnitude (Dulk 1985; Bastian, Benz, & Gary 1998), and this coherent process is possibly located in the small region around the above EUV flash.

According to the recent classification of microwave ZPs (Tan et al. 2014), the ZP burst here belongs to equidistant ZP, which is possibly originated from Bernstein wave mechanism (Rosenberg & Tarnstein 1972; Zheleznyakov & Zlotnik 1975; Maltseva & Chernov, 1989). In this mechanism, the energetic electrons with non-equilibrium distribution over velocities perpendicular to the magnetic field are located in a small source, where plasma is weakly and uniformly magnetized ($f_{pe} \gg f_{ce}$). These electrons excite longitudinal electrostatic waves at the sum of Bernstein mode frequency sf_{ce} and the upper hybrid frequency f_{uh} : $f = f_{uh} + sf_{ce} \approx f_{pe} + sf_{ce}$. Here, f_{pe} is the electron plasma frequency, f_{ce} is the electron gyro-frequency, s is the harmonic number. In such mechanism, all zebra stripes are

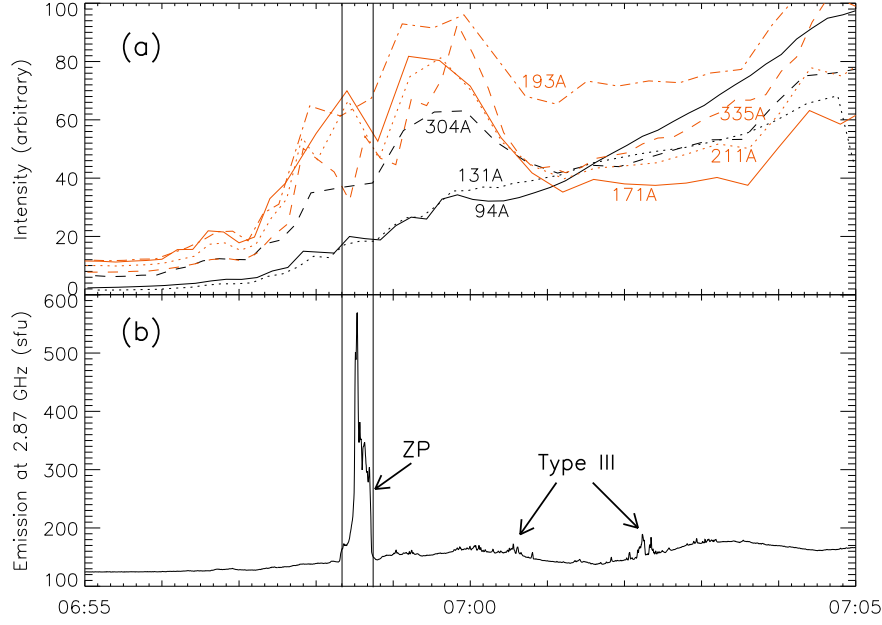


Fig. 4.— (a) is profiles of the integral EUV brightness in the white box at wavelengths of 94 Å, 131 Å, 171 Å, 193 Å, 211 Å, 304 Å, and 335 Å. (b) is the profile of microwave emission at frequency of 2.87 GHz centered at the ZP burst

generated from a small compact source (this point is compatible to the small EUV flash), and the emission is coherent, which is much stronger than that of the gyrosynchrotron radiation from the energetic electrons spiraling along magnetic field lines in the flaring region. The frequency separation between the adjacent zebra stripes is just the electron gyro-frequency: $\Delta f = f_{ce}$, it is a constant. By using the stripe frequency separation (90 MHz), we may directly measure the magnetic field strength in the source region. The value is about 32 Gs. From the emission frequency, the corresponding plasma density can be estimated as $8.4 \times 10^{10} \text{ cm}^{-3} - 1.3 \times 10^{11} \text{ cm}^{-3}$. These values are close to the conditions of solar corona near the flaring regions. The Bernstein wave mechanism requires large number of energetic electrons in a small-size compact source region. The production of these energetic electrons implies a fast particle acceleration taking place in the source region, and their propagation will carry out energy effectively from the source region which means a strong energy release process.

Generally, the flaring energy is released from

magnetic reconnection processes, and the large proportion of energy is first released into energetic non-thermal particles (Tandberg-Hanssen & Emslie 1988; Dere, Bartoe, & Brueckner 1989; Lin, Soon, & Baliunas 2003; Saint-Hilaire, & Benz 2005; Aschwanden, Dennis, & Benz 1998). These non-thermal particles can produce two kinds of emission bursts: (1) microwave bursts, when the non-thermal particles interact with the ambient plasmas, they may produce strong microwave burst by form of coherent mechanism which is always triggered by certain plasma instabilities. In this work, the non-thermal electrons are sufficient to trigger Bernstein waves, and the coupling between Bernstein wave and Langmuir waves makes the microwave bursts forming the extremely strong ZP burst. (2) EUV bursts, when the large number of non-thermal electrons precipitate and impact to the ambient plasma, they may deposit their energy and heat the plasma up to more than several million Kelvin by collision mechanism, and produce the strong EUV flashes. Both of the above two bursts make up the very small and super strong ZP explosion.

Therefore the impulsive EUV flash associated with the super strong ZP burst is a sudden explosion which can be regarded as a prompt signature of explosive energy release in the above small region. In fact, the flaring source region begins to brighten up from several small FBPs on the two ribbons before the flare onset (e.g. 06:57:37 UT). It is reasonable to suppose that these FBPs are the initial sites of magnetic reconnection and energy release. The ZP burst is just the strongest one which produced great number of energetic electrons and released powerful energy in a short time, and triggered the coherent microwave burst.

3. Conclusions and Discussions

From the above observations and physical analysis, we may get the following conclusions:

(1) A very short and super strong ZP burst observed simultaneously by two microwave telescopes located in China and Czech Republic just at the beginning of a solar M6.5 flare. This microwave ZP burst is so strong that its emission intensity exceeds several times of the underlying flaring continuum emission, and its brightness temperature exceeds 10^{11} K. It is possibly a coherent process triggered by the interaction between large number of non-thermal electrons and plasma instability in a small compact region. The non-thermal electrons are accelerated from a rapid magnetic reconnection in the source region.

(2) During the same time of the ZP burst, an EUV flash takes place with a sudden extra enhancement overlapped on the background continuous brightening observed at EUV images by AIA/SDO. The emission exceeds the saturation level at some EUV wavelengths. The flash region is only a small short bright point in the flaring region. Its existence indicates that there may be a rapid plasma heating and fast energy release in the source region.

(3) The simultaneity of the strong microwave ZP burst and the small EUV flash indicates that they may share a same small scale source region where rapid particle acceleration, violent energy release, and fast plasma heating take place simultaneously. It is an unusual explosion occurring in a small region centered in the flare source region just at the beginning of the solar flare.

The above results also indicate that a major so-

lar flare may start and develop from many small-scale bursting points, such as FBPs in this work. The small EUV flash associated to the ZP burst produce an extremely strong explosion in dimension of less than 2200×5000 km and plasma temperature up to several 10^6 K. The ZP burst is a strong coherent emission process which will transport energy away rapidly from the source region in form of energetic particles. And the small EUV flash reflects a fast conversion from non-thermal particles to heat the coronal plasmas to very hot in a small region and short period. The former may imply a rapidly particle acceleration in a small region, while the latter may imply a fast heating process in the solar atmosphere.

From letters of Drs. Bin Chen and Brian R. Dennis, they found that there was an obvious enhancement at 12-25 keV and 25-50 keV of RHESSI hard X-ray emission during the Zebra burst, and the homochronous RHESSI image at 25-50 keV shows that a non-thermal HXR footpoint source roughly coincides with the EUV footpoint brightening. This fact may be another evidence supporting the non-thermal origin of the ZP burst.

So far, as we have no high-resolution imaging observations at the corresponding microwave frequencies, we have no direct way to get the information of the source region of microwave ZP burst. When the new generation solar radio heliograph (such as the Chinese Spectral Radio Heliograph, CSRH, Yan et al. 2009) come into service, we may have much more opportunity to obtain directly the locations, geometrical structures, and magnetic fields in the source region of the microwave ZP bursts.

The authors would like to thank the referee for helpful and valuable comments on this paper. Drs. Bin Chen and Brian R. Dennis provide important results of RHESSI hard X-ray emission after the acceptance of this paper. We also thank the GOES, SDO, ORSC/Ondřejov and SBRS/Huairou teams for providing observation data. This work is supported by NSFC Grant 11273030, 11103044, 11103039, 11221063, 11373039, MOST Grant 2011CB811401, the National Major Scientific Equipment R&D Project ZDYZ2009-3, and the Grant P209/12/00103 (GA CR). This work was also supported by the Marie Curie PIRSES-GA-295272-RADIOSUN project.

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